JEWETT

Design of a Direct Current Generator and Switchboard for a Farm Power Plant

Electrical Engineering

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DESIGN OF A DIRECT CURRENT GENERATOR AND SWITCHBOARD FOR A FARM POWER PLANT

BY

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THESIS

FOR THE

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IN

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

ROY EARNEST JEWETT

ENTITLED DESIGN OF A DIRECT CURRENT GENERATOR

AND SWITCHBOARD FOR A FARM POWER PLANT

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF BACHELOR OF SCIENCE IN ELECTRICAL ENGINEERING

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INTRODUCTION

Having taken considerable interest in design and having been raised on a farm, I naturally wished to design a machine for use on the farm and to find what the difficulties were that come up and must be met.

The machine I chose to design is a small one for lighting and very small motors only. It would be situated near the house and therefore there would be only a little drop in transmission. On this account the machine is made flat compound.

DESIGN OF 10 K.W. D.C. GENERATOR AND SWITCHBOARD FOR A FARM POWER PLANT

The rating of the generator is to be 10 K.W. 110V., 4 pole, 1200 R.P.M. This voltage gives a total current of $\frac{10,000}{110}$ = 90.9 amperes. Assuming the ratio $\frac{\text{diameter x core length}}{10}$ (Steinmetz' coefficient) equal to five, the diameter and core length were made 10 and 5 inches respectively. The circumference is then $\pi D = \pi \times 10 = 31.4$ inches, making the pole pitch $\frac{31.4}{4} = 7.85$ inches. Using a polar embrace of 76.5% the pole face length peripherally equalls 76.5% of 7.85 = 6 inches.

The pole face then has an area of 5 x 6 = 30 sq.in. A density of 40,000 lines per sq. in. was assumed in the pole face, which gave the total flux, but as this was a little too large to agree with a convenient number of conductors, a density of 38,830 lines per sq. in. was used, which gave as total flux 38,830 x 30 = 1,165,000 lines.

In the following formula let – n = R.P.S., φ = total lines of flux from one pole, z = total number of conductors on armature face, E = terminal voltage, p = number of poles, and p' = the number of parallel paths in the armature, then $E = \frac{\varphi znp}{10^8 p'}$, but as the armature is to be lap wound $\frac{p}{p'} = 1$. Written again this formula becomes $z = \frac{E \times 10^8}{\varphi n}$ or $z = \frac{110 \times 10^8}{1,165,000 \times 20} =$ 472 armature conductors. Using 8 conductors per slot, wound 1 x 8 gives $\frac{472}{8}$ = 59 slots necessary. Conductors wound two coils per slot. With a total current of 90.9 amperes, the current in one path of the armature will be $\frac{90.9}{4}$ = 22.7

amperes. Allowing 500 circular mils per ampere, the area of the wire should be 500 x 22.7 = 11,350 circular mils. The nearest to this is #10 B.&S. wire with an area of 10,380 circular mils giving a current density of $\frac{10,380}{22.7}$ = 460 circular mils per ampere. But it was found easier to obtain the desired shape of slot, by using two #13 wires in parallel for the conductor instead of the one #10. Two #13 wires have the same area and therefore will give same current density as one #10 wire.

Width and Depth of Slots:- The diameter of #13 B.& S. double cotton covered wire is 0.083 in. Therefore the width of the slot must be twice this plus the insulation (.03 in.) on each side which makes it equal to 0.226 in. In order that the coil may be driven into the slot and thus made to stick, the slot is made wedge shaped, being 0.24 in. at the armature face and 0.22 in. wide at the bottom. The tooth pitch is $\frac{31.4}{59}$ = 0.532 in. Therefore the tooth at the armature face is 0.532 - 0.24 = 0.292 in. Since the conductors are wound 8 deep the slot depth will be 8 x 0.083 + 0.06 sunken-band + 0.03 insulation at bottom + 0.06 insulation at top + .03 insulation between the coils which gives 0.84 inches.

Length of Air Gap:- The ampere turns (A.T.) for the gap and teeth are usually about $1\frac{1}{4}$ times the ampere conductors per pole. The conductors per pole are $\frac{472}{4}$ = 118. And the ampere conductors per pole are 118 x 22.7 = 2680. Therefore the approximate A.T. for the gap and teeth are 1.25 x 2680 = 3350. The pole pitch is 6 in. and the tooth pitch is 0.532 in., therefore the teeth per pole are $\frac{6}{0.532}$ = 11.3.

Allow for fringing of the flux and call it 13 teeth through which the flux passes. The effective length of the armature, if a 3/16 in. air duct is put in,is .9 x 5 - 3/16 in. = 4.312 in. which allows 0.5 in. for air space between the laminations. This makes the effective area of each tooth 4.312 x 0.292 = 1.315 sq. in. The area of the 13 teeth per pole through which the flux passes is then 13 x 1.315 = 17 sq. in. The total flux being 1,165,000 lines, the flux density in the teeth is $\frac{1,165,000}{17}$ = 68,500 lines per sq. in.

The armature and teeth are to be punched from sheet steel of a thickness of 20 mils. and having the saturation curve as shown by the enclosed iron curves. For the density of 68,500 lines per sq. in., the ampere turns per inch are 8.9. Therefore the A.T. for the teeth are 8.9 x 0.84 = 7.5. Then 3350 - 7.5 = 3342 are the A.T. left for the gap. In the formula $0.3133\,\mathcal{B}\,l = A.T.$, let $\mathcal{B}$ be the flux density in lines per sq. in., l = the length of the gap in inches and A.T. = the ampere turns per pole necessary to force the required flux through the gap. Rewriting this formula $l = \frac{A.T.}{0.3133\,\mathcal{B}}$. The density in the gap is the flux divided by the area of the gap. The area of the gap is the mean between the area of the pole face and the area of the 13 teeth through which the flux passes.

Area of the pole face	=	30 sq. in.
Area of the 13 teeth	=	17 " "
		2)47
Area of Air Gap	=	23.5 sq. in.

Therefore the density ($\mathcal{B}$) is $\frac{1,165,000}{23.5}$ = 49,500 lines per sq. in. Substituting this value of $\mathcal{B}$ in the above

formula, the value of $l = \frac{3342}{0.3133 \times 49,500} = 0.215$ inch. Having found the approximate length to be 0.215 inch, a length of 3/16 inch was chosen which is 0.78 times the width of the slot. From the same formula, solving for A.T. we have, A.T. $= 0.3133 \times 49,500 \times 0.1875 = 2910$ per pole for the air gap.

Commutator:- Having decided upon 59 slots, and two coils per slot, there must be 118 segments in the commutator, which is equal to 29.5 segments per pole. Therefore the volts per segment $\frac{110}{29.5} = 3.73$. Making the diameter of the commutator 4/5 that of the armature gives as the diameter $4/5 \times 10 = 8$ inches. The circumference is $\pi D = \pi \times 8 = 25.2$ inches. The width of a segment including insulation is then $\frac{25.2}{118} = 0.213$ inch. Allowing 0.03 inch for insulation leaves the width of the segment proper to be 0.183 inch.

Since all of the current must pass in two sets of brushes and out at the other two, the amperes per set of brushes are $\frac{90.9}{2} = 45.45$. Allowing 40 amperes per sq. in. of brush contact, this gives a brush contact of $\frac{45.45}{40} = 1.135$ sq. in. per set of brushes. The brush should cover from 2 to 3 segments. Making them 0.5 in. wide they will cover $\frac{0.5}{0.213} = 2.35$ segments. The length to give the required contact area must be $\frac{1.135}{0.5} = 2.27$ inches for each set of brushes. Two brushes were used, each 1 1/8 in. long, which makes the length of the two brushes together 2.25 in. Then the area of contact is $2.25 \times 0.5 = 1.125$ sq. in. and the amperes per sq. in. of brush contact are $\frac{45.45}{1.125} = 40.4$. Allowing 1/8 in. between the brushes, 3/8 in. next to armature and 0.5 in. outside of

brushes gives the total length of commutator to be $2.25 + 1/8 + 3/8 + 1/2 = 3.25$ in. Assuming a pressure of 1.5 lb. per sq. in. upon the brushes, the volts drop due to the brushes was read off from a set of curves for various pressures plotted between volts drop and amperes per sq. in. of contact. This value was found to be about 2 for 40.5 amperes per sq.in. of contact. The watts lost then were $EI = 2 \times 90.9 = 182$ watts.

The watts lost due to friction between the commutator and brushes was determined from the following formula

$$\text{Watts lost} = \frac{0.3 \times 1.5 \times B \times \frac{\pi D n}{12} \times 746}{33{,}000} = 0.00267\, B D n,$$

where, 0.3 is the coefficient of friction bewteen brushes and commutator, B is the area of contact, D is the diameter of the commutator, n is the revolutions per minute, and 1.5 is the pressure on the brushes in lb. per sq. in. Substituting the values already determined,

$$\text{Watts lost} = 0.00267 \times 2.25 \times 8 \times 1200 = 58$$

Therefore the total watts lost $58 + 182 = 240$

Thomson in his Dynamo Electric Machinery, Volume I gives the formula $\theta = \dfrac{46.5 \times \text{watts lost}}{\text{Radiating Surface} \times (1 + .0005 \times \text{peripheral speed})}$ where θ is the rise in temperature in degrees centigrade and should not exceed 60. The surface of the commutator is $\pi \times 8 \times 3.25 = 82$ sq. in.

$$\text{Therefore } \theta = \frac{46.5 \times 240}{82 \times (1 + .0005 \times 2520)} = 60.$$

Armature Core:- The teeth are nearly 1 inch long, which leaves the armature inside the teeth over 8 in. in diameter. By the cut and try method it was found that a density

in the armature body of 70,750 lines per sq. in. gave a necessary area of 8.23 sq. in. which could be supplied by using a radial depth of armature core equal to 1.91 in., for the effective length, allowing for a 3/16 in. air duct is 4.312 in. The area = 4.312 x 1.91 = 8.23 sq. in.

The flux divides and goes both ways through the armature so only one half of it is used in getting the density i.e. $\frac{1,165,000}{2 \times 8.23} = 70,750 = B$ for the core. The radial depth of the core being 1.91 inches, leaves the internal diameter 4.5 in. The internal circumference is then $\pi \times 4.5 = 14.15$ in. and the external circumference of armature body is $8.32 \times \pi = 26.2$. The average of these two being $\frac{1}{2}(26.2+14.15) = 20.125$ and 1/4 for each pole = 1/4 of 20.125 = 5.031 in. But since the M.M.Fs. from the different poles act in series only 1/2 of this or 2.52 in. is the path through the armature for a single pole. The armature is built of sheet steel punchings as mentioned before, and the A. T. per inch taken from the enclosed iron curves is 10.2 for a density of 70,750. Therefore the A.T. per pole for the armature core are 10.2 x 2.52 = 25.7

Armature Resistance:- The conductors should extend out beyond the end of the armature about 3/4 in. so as to avoid any cutting on the edges. In order to wind properly they must be brought out after that at an angle of 45° as shown by figure I.

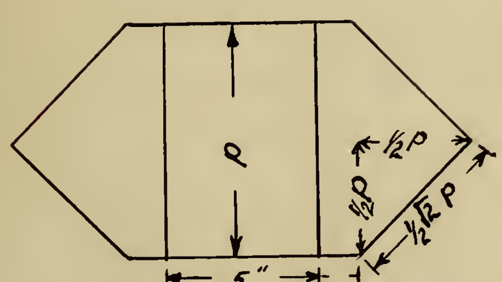


Figure I.

This will make the length of one turn equal to $2\times5 + 4(3/4'' + \frac{1}{2}\sqrt{2}p) = 10 + 4(3/4'' + \frac{1}{2}\sqrt{2}\times7.85) = 35.2$ in. The total number of conductors being 472, the conductors per pole are $\frac{472}{4} = 118$ between plus and minus or 59 turns. Considering $\rho = 12$ ohms per mil foot the resistance of the armature is $\frac{59 \times 35.2}{10360 \times 4} = 0.05$ ohms. The IR drop in the armature is $90.9 \times 0.05 = 4.55$ or 5 volts.

Armature Heating:- The heating in the armature is due to I^2R loss which in this machine is equal to $\overline{90.9}^2 \times 0.05 = 413$ watts. The heating should not be so great that more than 1.5 watts need be radiated per sq. in. of surface. The radiating surface on the armature is the face counted as a full surface and the ends counted as half surfaces. Therefore the radiating surface is

$\pi \times 10 \times 5$	= 157	sq. in.	for the face.
$\frac{\pi D}{4} \times 10 \times 5$	= 78.5	" "	for one end.
$\frac{\pi D}{4} \times 10 \times 5$	= 78.5	" "	one side of air duct.
	314	" "	total radiating surface.

Therefore the watts per sq. in. of radiating surface are $\frac{413}{314} = 1.3$ watts. Well within the limit.

Pole Core:- The pole must have dimensions such that there is room for the windings between the poles. It was found that it was necessary to make the pole 5 in. long and to wind the conductors 1.5 inches deep. An air space of 0.5 in. was left next to the core on each side. The diagram on the next page is drawn to 3/4 scale and shows that the above dimensions can be used, by using a pole core 4.5 in. in diameter, which makes the area of the pole $\frac{\pi}{4} \times \overline{4.5}^2 = 15.9$ sq. in.

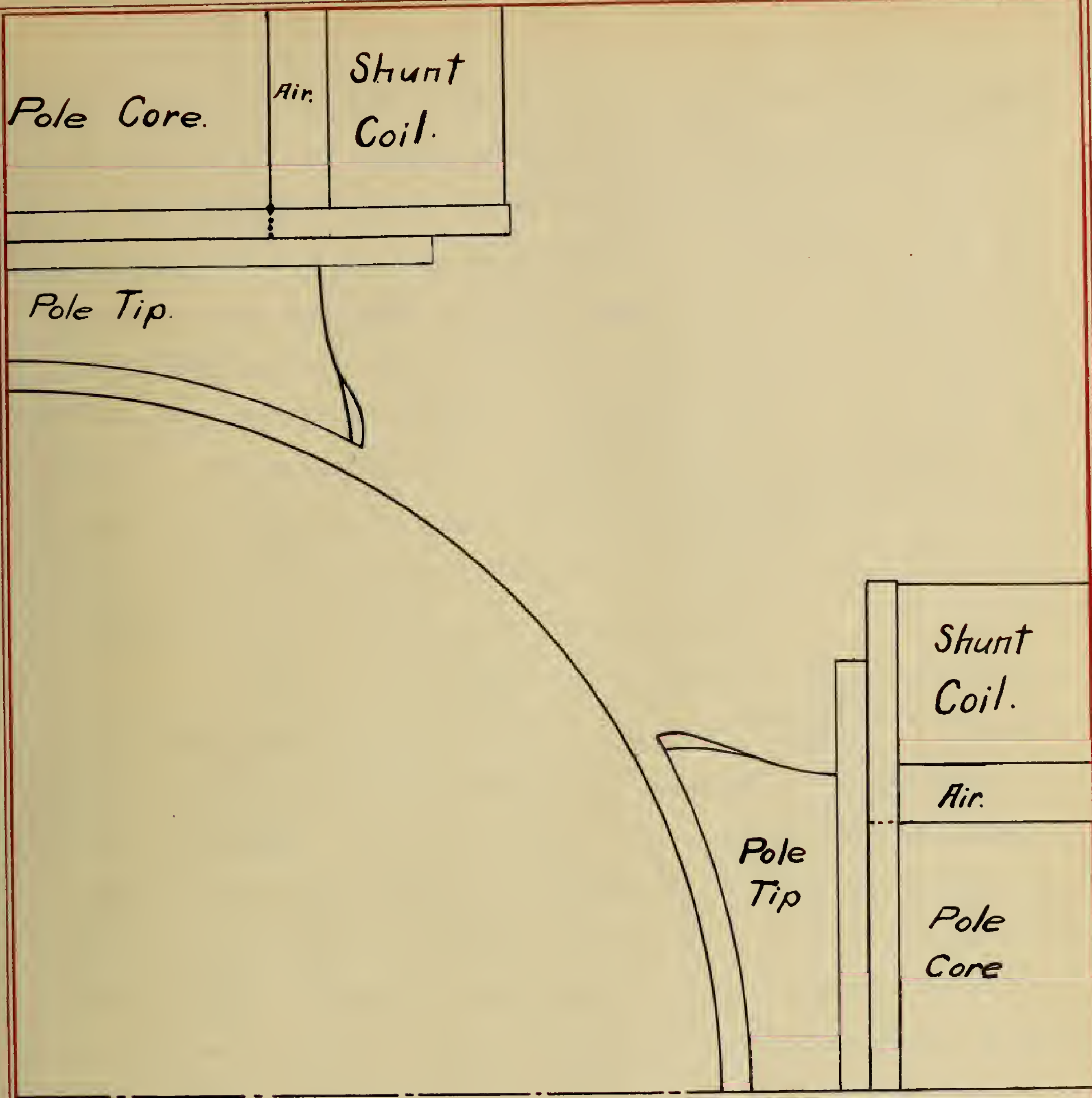


Diagram Showing

Fitting of Shunt Field Winding.

Scale - 3/4" = 1"

The flux for the pole core is 1.2 x 1,165,000 = 1,398,000 lines, where 1.2 is the leakage factor, which is used because a part of the flux that passes through the yoke and pole core leaks through the air gap and does not cut the conductors. The density is then $\frac{1,398,000}{15.9}$ = 88,000 lines per sq. in. Using cast steel for the core and referring to the enclosed iron curves it is found that at a density of 88,000, the A.T. per inch are 22.86. Therefore the A.T. per pole needed for the pole core are 5 x 22.86 = 114.3. The length here assumed will be checked when the exact size of the shunt and series wire and the exact number of turns of each have been determined.

Yoke:- In the yoke the flux has two paths as in the armature, therefore the flux per path is $\frac{1,165,000}{2}$ = 699,000. The yoke should be wide enough to extend out over the armature windings to protect them. The armature is 5 in. long and as shown under Armature Resistance the windings extend out beyond the end of the armature 3/4" + 1/2 p = 3/4" + 3.93" = 4.68" on each end. Therefore the width of the yoke should be at least 5 + 2 x 4.68 = 14.36 in. Make it 14.5 inches wide. A suitable depth of yoke would be 2 in. which gives the area to be 2 x 14.5 = 29 sq. in. Therefore the density is $\frac{699,000}{29}$ = 24,100 lines per sq. in. Using cast iron for the yoke and referring to the iron curves it is found to take 17.5 A.T. per inch of length.

The distance from the center of the armature to the center of the yoke is composed of lengths as follows:-
Armature and teeth 5 inches, air gap 3/16 in., pole piece 3/4in. pole core 5 in., yoke 1 in. making in all 12 inches. The length

of the flux path through the yoke per pole is then $\frac{12 \times 2 \times \pi}{2 \times 4} =$ 9.45 inches. The total ampere turns for the yoke are then 9.45 x 17.5 = 166 per pole.

Having determined the ampere turns per pole for each part of the magnetic circuit they will now be summed up.

Part	A.T.
Air Gap	2910
Teeth	8
Armature body	22
Pole Core	114
Yoke	166
Total A.T. at no load	3220

Shunt Wire:- Knowing the total number of A.T. for the shunt field, we can now find the size of wire needed and check on the length of pole core used. The four shunt coils are to be inseries, therefore the volts per coil are $\frac{110}{4} = 27.5$. Let e be the voltage impressed per coil, ρ = the specific resistance in ohms per mil foot equal to 12, l = length of the wire in feet, T = the number of turns, A = the number of amperes flowing, a = the area of the wire in circular mils and R = the total resistance of one coil. Then,

$$\frac{e}{R} = A = \frac{e}{\rho \frac{l}{a}} T = \frac{A.T.}{T}$$

$$\text{or} \quad \frac{e}{\rho \frac{l}{a}} = A.T. \text{ and solving for } a,$$

$$a = \frac{A.T. \times \rho \times l}{e}$$

The outer diameter of the windings is 4.5 + 1 + 3 = 8.5 inches. The inside diameter is 5.5 inches. Therefore the mean diameter is 7 in. and the

mean length of turn is $7 \times \pi = 22$ in. Substituting in the above equations the values now determined

$$a = \frac{3226 \times 22 \times 12}{27.5 \times 12} = 2575 \text{ circular mils.}$$

This corresponds very closely to #16 B.& S. wire which has an area of 2,583 circular mils. In order to have a means of varying the resistance in the field and thereby the current flowing, thus changing the emf. generated, a size larger wire (#15 B.& S.) is used and a rheostat placed in series with the field.

The area of #15 B.& S. wire is 3,253 circular mils. Allowing 1000 circular mils per ampere, the current in the shunt field will be practically 3.3 amperes. The number of turns needed will be $\frac{A.T.}{A.} = \frac{3220}{3.3} = 975$, practically 1000. These were wound $20 \times 50 = 1000$. The diameter of #15 B.& S. double cotton covered wire is 0.066 practically 0.07 in. Therefore the length of the field pole used by the shunt field windings is $50 \times 0.07 = 3.5$ inches and the width on each side of the pole used by the windings is $20 \times 0.07 = 1.4$ in.

So far all of the calculations have been made for the no load conditions. Now calculations must be carried out to find the number of A.T. needed at full load. The difference between the full load and no load A.T. must be furnished by the series field. The voltage that must be generated at full load is the terminal voltage (110 v.) plus the IR drop in the armature plus the IR drop in the series field plus the IR drop in the brushes. The IR drop in the armature has been found to be at full load 5 volts. The IR drop in the series

field was assumed to be about 1/2% of the terminal voltage which is practically 0.6 volts. The drop in the brushes was taken from a curve plotted between volts drop and amperes per sq. in. of brush contact for carbon brushes having a pressure of 1.5 lb. per sq. in. From this curve the drop was found to be 2 volts. Therefore the voltage generated at full load must be 110 + 5 + 0.6 + 2 = 117.6 practically 118 volts.

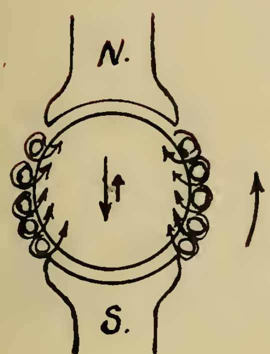
From this value of voltage the flux that is needed to generate it was found from the equation

$$\varphi = \frac{E \times 10^8}{z\ n} = \frac{118 \times 10^8}{472 \times 20} = 1,250,000 \text{ lines.}$$

This is the flux for the teeth and air gap. The flux for the armature body is 0.5 x 1,250,000 = 625,000 lines. Applying the leakage coefficient, 1.2, the flux for the pole core is 1.2 x 1,250,000 = 1,500,000 lines and that for the yoke is $\frac{1,500,000}{2}$ = 750,000 lines.

The densities for each part of the magnetic circuit were then found by dividing the flux for that part by the area of the path through that part. Then referring to the iron curves as was done for the no load conditions, the ampere turns per unit length were found for the respective densities and, when multiplied by the length of the path through each part, gave the total ampere turns for that part. Adding the ampere turns for the separate parts gave the total ampere turns.

Part	Density	Ampere Turns per Unit Length	Total A.T for each part
Armature	76,000	12.7	32
Teeth	73,500	11.5	10
Air Gap	53,200		3125
Pole Core	94,400	38.1	190
Yoke	28,850	19.1	180
		Total	3537



Armature Reaction:- The current flowing through the turns of the armature cause a magneto-motive force, a component of which directly opposes the M.M.F. of the field. As shown by the accompanying diagram, the ampere turns on the armature face between the poles are the ones that produce this component. Therefore in order to obtain the desired flux, the ampere turns on the field core must be increased sufficiently to overcome this armature reaction. Since there are 472 conductors and 22.7 amperes per circuit in the armature, the ampere conductors per pole are $\frac{472 \times 22.7}{4} = 2680$. The ampere conductors beneath the pole are 76.5% of 2680 = 2050. Therefore the ampere conductors between the poles that set up the armature reaction are 2680 - 2050 = 630. Or 630 A.T., for the conductors passing between two poles on one side of the armature come between two similar poles on the other side, each pair forming a turn. These 630 ampere turns per pair of poles are to be wound half on each pole or 315 A.T. per pole to compensate for armature

reaction.

Adding these to the former total, viz. 3537 A.T. the sum is 3852 A.T. needed at full load. The A.T. furnished by the shunt field are, as found, 3224. Subtracting these from the total gives 3852 - 3224 = 628 A.T. which must be furnished by the series field. Since the current at full load is 90.9 amperes, the number of turns for the series field will be $\frac{628}{90.9} = 6.9$. But there must be a half turn in order to be in position to start winding the next pole, therefore it is made 7.5 turns per pole. A strip 0.05 x 1.5 inches was used giving an area of 0.075 sq. in. or 95,500 circular mils. This gives a current density of $\frac{95{,}500}{90.9} = 1050$ circular mils per ampere which is necessary on account of heating. The turns are wound on edge. Allowing 0.02 in. for insulation the width of the strip is 0.05 + 0.02 = 0.07 in. and the length of pole core occupied is 8 x 0.07 = 0.56 inches. The depth of winding is 1.5 + 0.02 = 1.7 inches. This is permissable because the series winding is to be placed next to the yoke.

The length of the pole core used can now be checked accurately. The following lengths on the core have been determined:-

length of core occupied by shunt field	3.5 in.
length of core occupied by series field	.56 in.
	4.06 in.

length of core assumed	5.00	inches
length of core occupied by windings	4.06	"
length left	0.94	"
Air space next to yoke	0.5	"
Air space between shunt and series field	0.44	"
	0.25	"
Space next to pole piece	0.19	inch which is good.

Resistance and Heating of the Shunt Field:- The resistance per foot of #15 wire is 0.003552. The mean length of a turn has been found to be 22 inches, and the number of turns 1000. Therefore the resistance per coil is $\frac{0.003552 \times 22 \times 1000}{12} = 6.5$ ohms. The total resistance of the field is 4×6.5 ohms $= 26.0$ ohms. The total loss is the shunt field is $26 \times \overline{3.3}^2 = 284$ watts. The IR drop in the shunt field is $3.3 \times 26 = 85.5$ volts. The difference, $110 - 85.5 = 24.5$ volts must be in the rheostat. Therefore the resistance of the rheostat must be $\frac{24.5}{3.3} = 7.43$ practically 7.5 ohms. Use a 25 ohm rheostat.

The heating of the field is due to the I^2R loss. Let θ be the rise in temperature above room temperature in degrees centigrade, then $\theta = K\frac{W}{A}$ should not exceed 50°, where $K = 60$, $W =$ the watts lost and $A =$ the area of the cooling surface. $W = 284$ watts. The outside area counts as full area, while the inside area counts as half its value for radiating heat.

The outside area $\pi \times 8.5 \times 3.5 = 93.5$ sq. in.

The inside area $(\pi \times 5.5 \times 3.5)\frac{1}{2} = 30.3$ " "

$$\begin{array}{r} 123.8 \\ 4 \\ \hline 495.2 \end{array}$$ " " for the 4 coils.

Therefore $\theta = 60 \frac{284}{495} = 35^\circ$ rise in temperature, which is well within the limit.

Resistance and Heating of the Series Coil:- There are 628 ampere turns needed in the series field and, as there are to be 7.5 turns, a part of the 90.9 amperes load current must be shunted out of the field leaving $\frac{628}{7.5} = 83.7$ amperes, upon which the heating depends. The area of the strip is 95,500 circular mils and the mean length of a turn is 22 inches therefore the resistance of the four coils in series is $\frac{4 \times 22 \times 7.5 \times 12}{95,500 \times 12} = 0.00692$ ohms. The drop in voltage is $83.7 \times 0.00692 = 0.58$ volts, very nearly the assumed value of 0.6 volts used to calculate the generated full load voltage.

The watts lost $\overline{83.7}^2 \times 0.00692 = 48.5$ watts.

The radiating area is composed of the outside surface counted at full value and the inside surface counted at half value.

Outside surface for radiation $\pi \times 8.5 \times 0.56 = 15$ sq. in.

Inside surface for radiation $\frac{1}{2}(\pi \times 5.5 \times 0.56) = 4.85$ sq. in.

19.85 sq. in.

Therefore the total radiating surface is practically 20 sq. in. per coil or $4 \times 20 = 80$ sq. in. for the four coils.

Using the formula $\theta = K \frac{W}{A}$ as was done in the shunt field calculation

$$\theta = 60 \times \frac{48.5}{80} = 36.4^\circ \text{ C.}$$

rise in temperature above room temperature for the series field. This is well within the limit of 50° generally used.

Saturation or Magnetization Curve:- Taking the densities of the different parts of the magnetic circuits at densities from 0.5 up to 1.25 normal densities, the ampere turns necessary to produce them were found for each part and their sum gave the A.T. necessary to produce the corresponding values of voltage from 0.5 up to 1.25 normal voltage. The results are tabulated below and a curve was drawn between voltage and ampere turns.

Saturation Curve Data

E 55 0.5 normal Voltage	Armature body	Teeth	Gap	Pole Core	Yoke	Total
Density	32,360	34,250	25,875	44,000	12,050	
A.T. per in.	1	1.5		1.6	3	
Total A.T.	1	0.5	1530	3	11	1546
E 82.5 volts. 0.75 normal voltage.						
Density	48,500	51,500	38,800	66,000	18,975	
A.T. per in.	1.7	1.8		3.25	4.5	
Total A.T.	1.5	0.5	2280	6.3	17	2305
E 137.5 volts. 1.25 normal voltage.						
Density	80,800	85,500	64,700	110,000	30,125	
A.T. per in.	15.25	7.5		80	10.5	
Total A.T.	6	2.5	3800	158	40	4007

Efficiency:- The losses in a direct current generator are:- I^2R losses in the armature windings, in the series and shunt fields, and in the brushes, friction loss on the commutator and bearings, windage, and hysteresis and eddy current losses in the teeth and armature. These losses have all been determined but the hysteresis and eddy current and the bearing friction and windage. Curves were found in Thomson's Dynamo-Electric Machinery, Volume I, pages 103 and 105 which gave the watts lost per cubic inch per cycle by hysteresis and by eddy currents. The teeth have a density of 68,500 for which density the hysteresis loss using $n = 0.004$ is 0.0175 watts per cu. in. per cycle and the eddy current loss using laminations 20 mils in thickness is 0.000075 watts per cu. in. for one cycle and varies as the square of the number of cycles. Since there are 59 teeth each having an area of 1.315 sq. in. and a depth of 0.84 in. The volume of the teeth is $1.315 \times 0.84 \times 59 = 65$ cu. in.. Therefore the hysteresis loss in the teeth is $0.0175 \times 65 \times 40 = 45.5$ watts and the eddy current loss is $0.000075 \times 65 \times \overline{40}^2 = 7.8$ watts. The armature density was 70,750 at which density the hysteresis loss for laminations 20 mils thick is 0.0163 watts per cu. in. per cycle and the eddy current loss is 0.00007 watts per cu. in. for one cycle and varies as the square of the number of cycles. Since the armature body has an area of 8.23 sq. in. and the mean circumference of the armature body is practically 20 in., the volume is $8.23 \times 20 = 164.6$ cu. in. Therefore the hysteresis loss in the armature is $0.0163 \times 164.6 \times 40 = 107.5$ watts and the eddy current loss is

$0.00007 \times 164.6 \times \overline{40}^{2} = 18.4$ watts. The eddy current and hysteresis losses will remain practically constant for all loads so they are here summed up. Their sum gives:-

$45.5 + 7.8 + 107.5 + 18.4 = 180$ watts hyst. & eddy current.

The number of cycles (40) used above is the number of revolutions per second multiplied by the number of pairs of poles i.e. $\frac{4}{2} \times \frac{1200}{60} = 40$ cycles per second.

By summing up all the losses of the machine at the various values of load from 0.5 load up to 1.25 load and finding the ratio of the output over the output plus the losses, the electrical efficiency at the various loads is obtained and a curve plotted between percent efficiency and percent full load.

Efficiency Data

Losses	0.25 Load	0.5 Load	0.75 Load	Full Load	1.25 Load
Armature I R	26	104	232	413	645
Series Field I R.	4	15	32	57	89
Commutator Loss	58	58	58	58	58
Shunt Field I R.	284	284	284	284	284
Brush I R.	11	45	102	182	284
Hyst & Eddy Current	180	180	180	180	180
Friction & Windage	300	300	300	300	300
Sum	863	986	1188	1474	1840
Output	2500	5000	7500	10000	12500
Output + Losses	3363	5986	8688	11474	14340
Eff. = $\frac{\text{Output}}{\text{Output + Losses}}$	74.3%	83.5%	86.25	87	87

Assuming the value of friction and windage loss to be 3% of full load output, which is the value given in Thomson's Dynamo-Electric Machinery Volume I. for this size of machine.

Design of the Direct Current Generator.

Type of Machine:- Belted: 4 Poles; 10 Kw; 1200 R.P.M.

110 Volts; 90.9 Amperes.

Type:- Compound, Flat.

Voltage:- No Load - 110 Volts, Full Load - 110 Volts.

Armature.

diameter at face.	10
periphery.	31.4
pole pitch at armature face	7.85
length between core heads	1.85
Steinmets coeff. (d x cl ÷ Kw.)	5
thickness of core sheets	20 mil
number of ducts	1
effective length of core	4.312
radial depth of core body	1.91
internal diameter of core	4.5
number of slots	59
width of slots at bottom	0.22
width of slots at top	0.24

Armature (cont)

minimum width of tooth	0.292
total number of face conductors	472
number of circuits	4
type of winding	lap
depth of slots	0.84
no. of cond. in series between plus & minus	118
size of conductors 2 in 11	#13
diameter of conductor insulated	0.083
mean length of conductor per turn	35.2
pitch of winding (front and back) inches	7.448
pitch of winding, no. of teeth	14
arrangement of cond. in slot.	

Dimensions (cont)

length of active conductor per volt	5.9
total insulation between cond. & core.	0.045
peripheral speed (ft. per min.)	3140

Gap.

length at center from iron to iron	0.1875
diameter of bore of field	10.375

Magnet Core.

length radially	5
section	D=4.5
area of section of core	15.9

Pole Pieces.

length parallel to shaft	5
length of pole arc	6
polar embrace	76.5%
area of pole face	30

Coil.

size of shunt wire	#15
section area of wire	3,253 c.m.
mean length of one turn	22
compound conductor section	0.05x1.5

Commutator Brushes.

number of sets	4
number in one set	2
length, side by side	2.25
width(peripherally) of brushes in inches	0.5
number of segments covered	2.18
size of contact surface (sq. in.)	1.125
total area of contact (one polarity)	2.25

Yoke.

outside diameter	26
inside diameter	22
thickness	2
length parallel to shaft	14.5

Dimensions (cont.)

Yoke (cont.)

area of section	29

Commutator.

diameter	8
length of segment over all	3.25
area of cylindrical surface	82
active length of segment	2.25
number of segments	118
width of segments	0.229
useful depth of segment	1 in.
thickness of insulation between segments	0.03
peripheral speed (ft. per min.)	2520

Electrical

Electrical Armature

emf. per circuit, no load	110
emf. per circuit, full load	110
type of winding	lap
no. of turns per commutator segment	2
amperes per circuit of winding	22.7

Reactions

circular mils per ampere	460
IR drop (lost volts) in armature	5
ohms brush to brush at 50 C.	0.05

Commutator

average volts between segments	3.73
frequency of commutation	

Electrical Reactions (cont.)

Commutator (cont.)

amperes per sq.in. of brush contact	40.4
IR drop (lost volts) due to brush contact	2

Field Coils.

type	taped
no. of coils in series	4
mean length of one turn	22
total resistance (at 50 C.)	26
amp. full load (shunt excit)	3.3
rheostat resistance	7.5
IR drop in rheostat	24.5

Compound Winding.

no. of turns in series per coil.	7.5
mean length of one turn	22
total resistance (at 50 C.)	0.00692
amperes, full load	90.9
circular mils per ampere	1050
IR drop (lost volts) in series coil	0.63

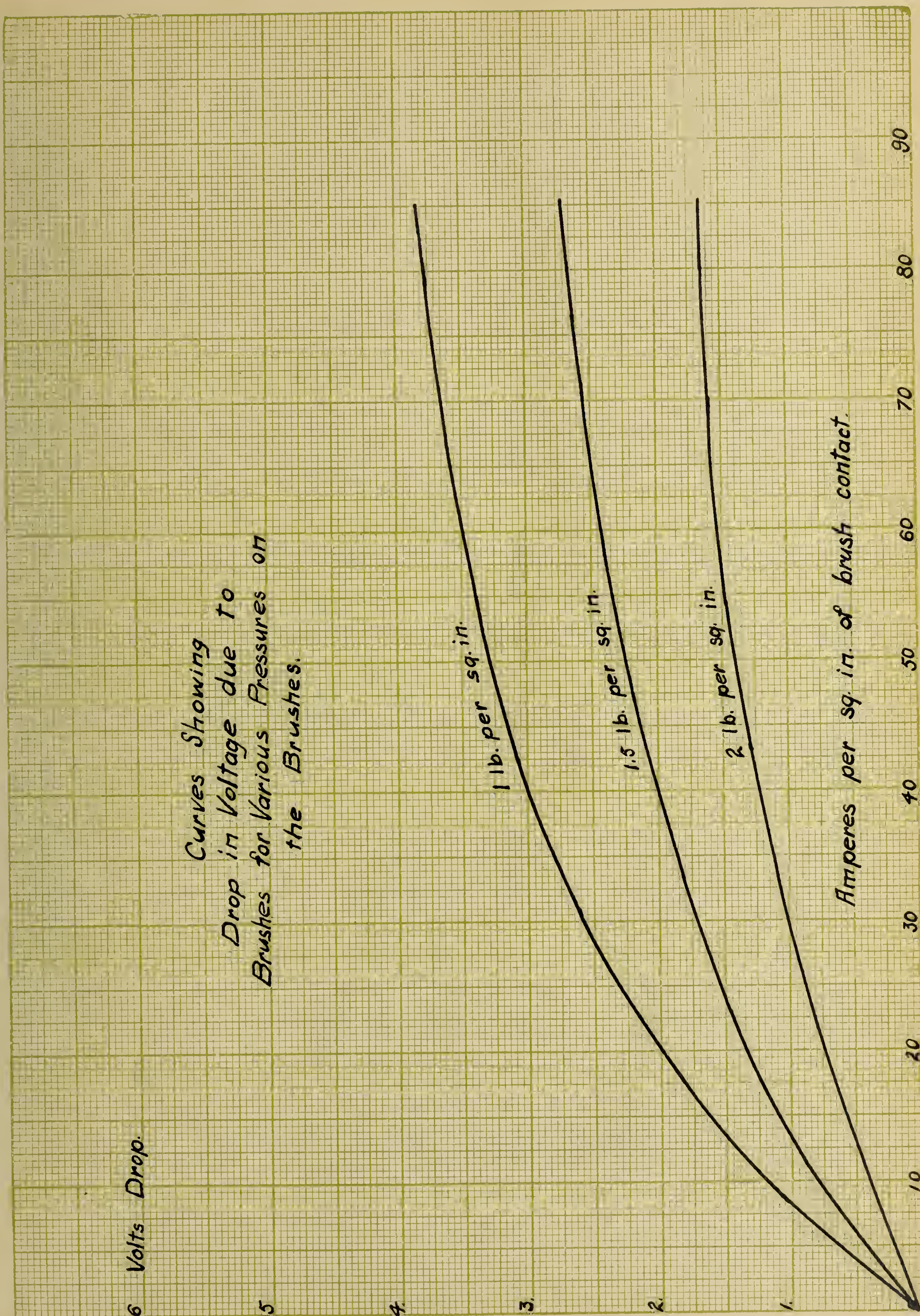
Reactions.

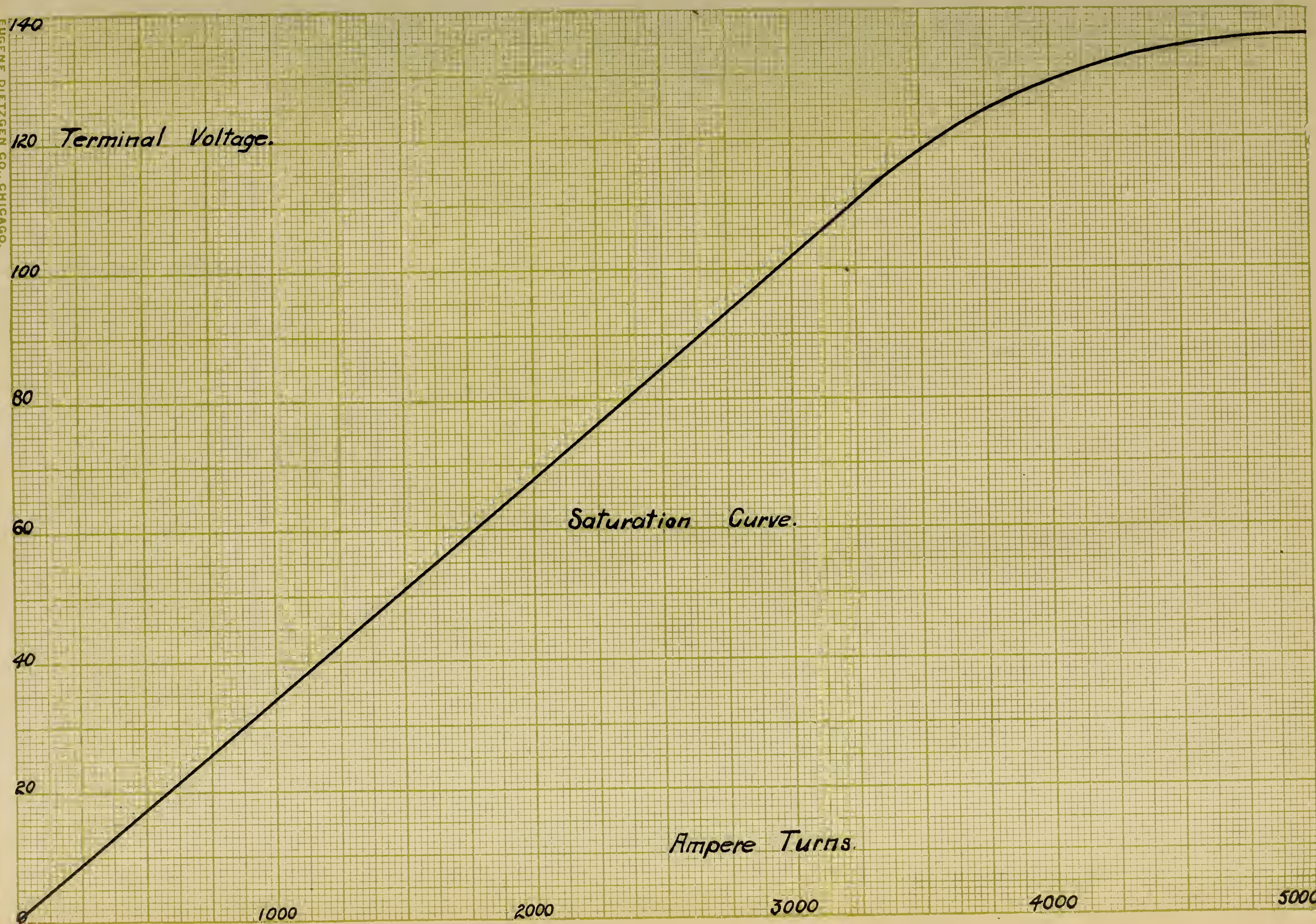
Armature.

ampere conductors per pole	2680
ampere cond. beneath pole	2050
ampere cond. between poles	630
ampere cond. per in. of periphery	342
stiffness ratio	1.42
reaction conductors per pole	630
reaction ampere turns per pole	315

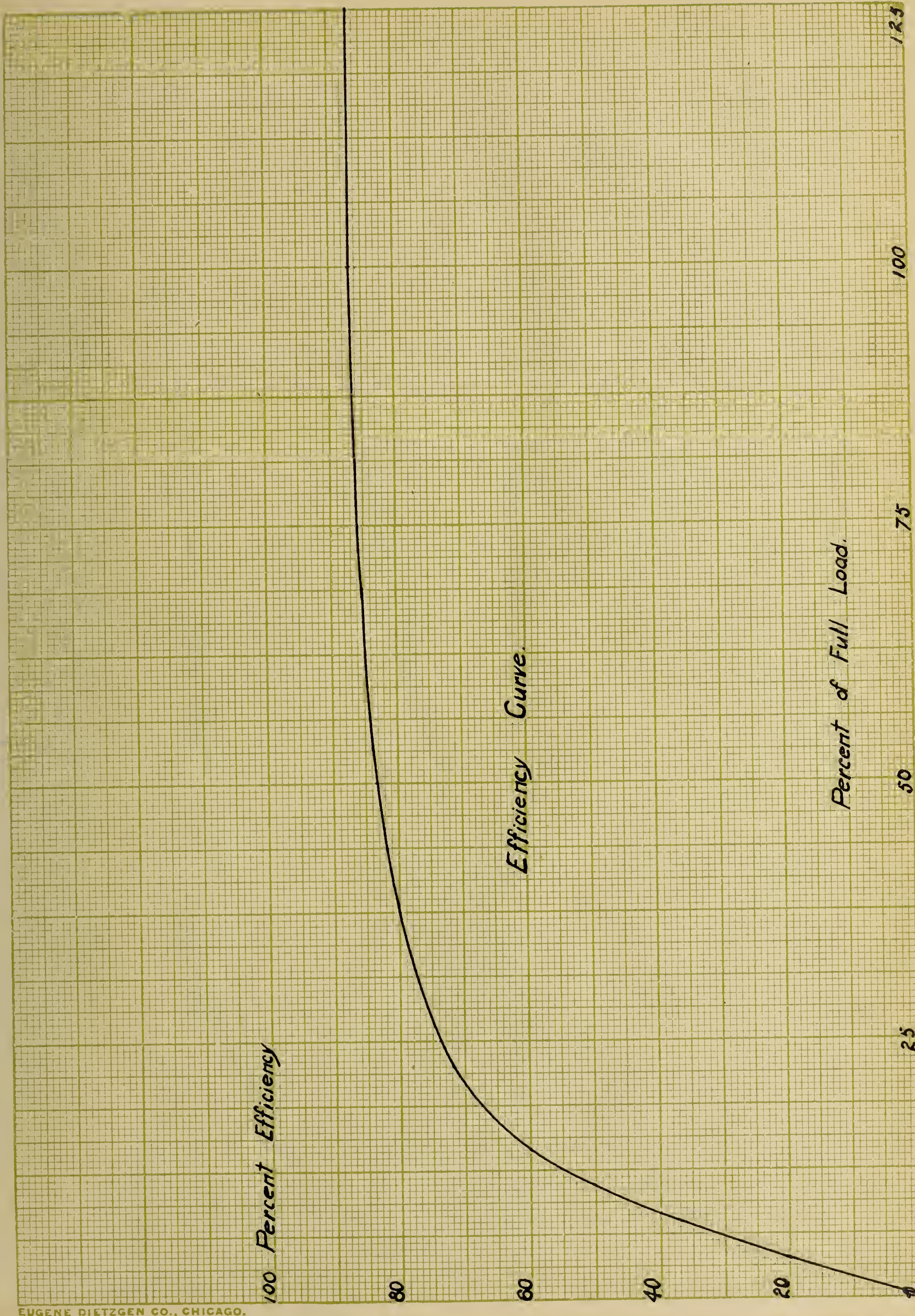
	Part.	Material.	Flux per Pole. (megalines).	Section Area.	Flux Density.	Mean Magnetic Length.	A.T. per Unit Length (from curves).	Total A.T. Needed.
At No Load.	Armature	Sheet Steel	0.5825	8.23	70,750	2.52	10.2	26
	Teeth.	Sheet Steel	1.165	17	68,500	0.84	8.9	8
	Air Gap.	Air.	1.165	23.5	51,750	0.1875		2910
	Pole Core.	Cast Steel	1.398	15.9	88,000	5	22.86	114
	Yoke.	Cast Iron.	0.699	29	24,100	9.45	17.5	166
					Total A.T. Needed at No Load =			3224
At Full Load.	Armature.	Sheet Steel	0.625	8.23	76,000	2.52	12.7	32
	Teeth.	Sheet Steel	1.25	17	73,500	0.84	11.5	10
	Air Gap	Air.	1.25	23.5	53,200	0.1875		3125
	Pole Core.	Cast Steel.	1.5	15.9	94,400	5	38.1	190
	Yoke.	Cast Iron.	0.75	29	25,850	9.45	19.1	180

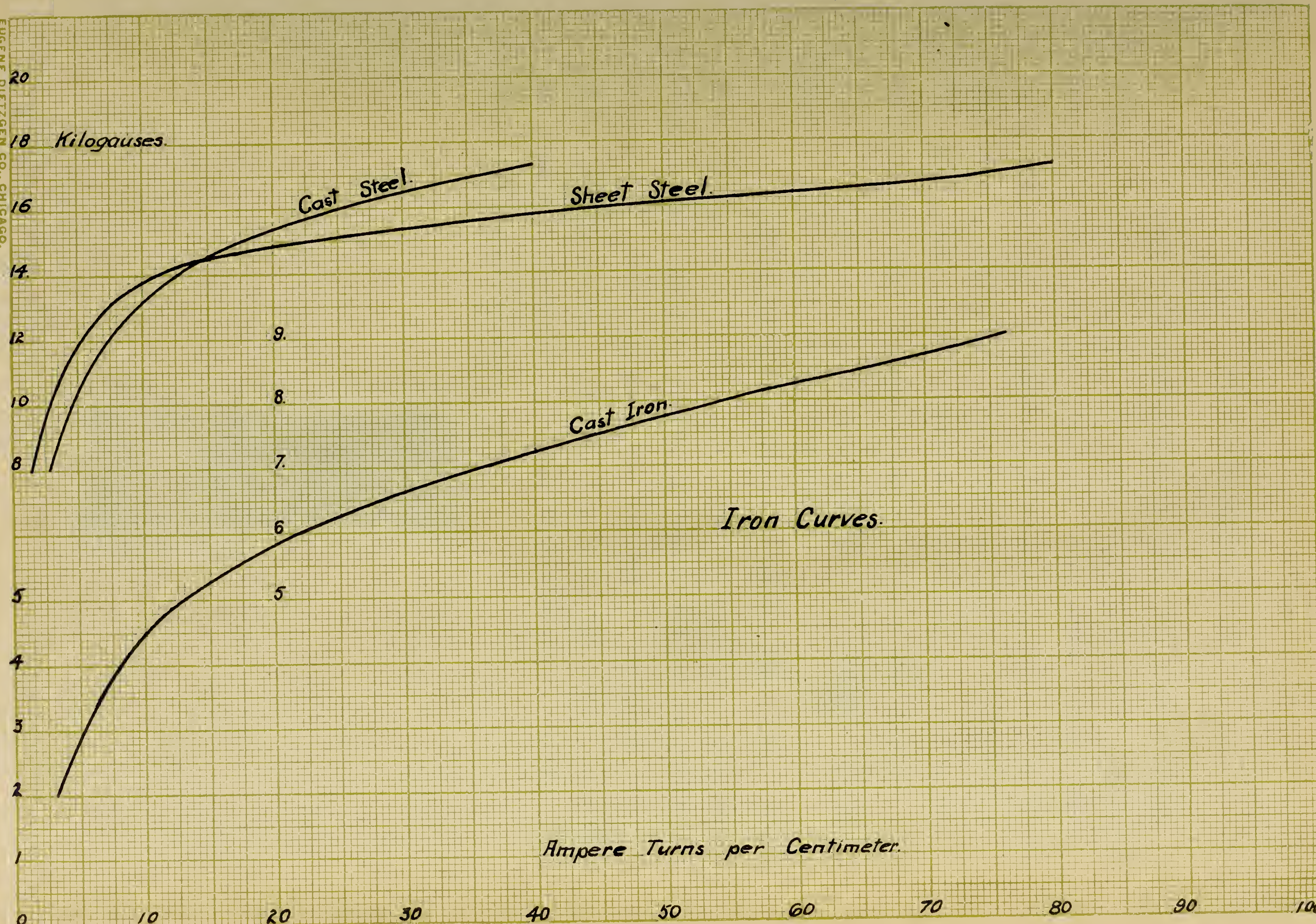
Total A.T. Needed at Full Load.	3537
Add to Compensate for Armature Reaction.	3852
Deduct Shunt A.T. at No Load	3224
Series A.T. = Difference.	628


Curves Showing
Drop in Voltage due to
Brushes for Various Pressures on
the Brushes.
1 lb. per sq. in.
1.5 lb. per sq. in.
2 lb. per sq. in.
Amperes per sq. in. of brush contact.
Volts Drop.
6
5
4.
3.
2.
1.
10
20
30
40
50
60
70
80
90



EUGENE DIETZGEN CO., CHICAGO.


Efficiency Curve.
Percent Efficiency
Percent of Full Load.
100
80
60
40
20
0
25
50
75
100
125
EUGENE DIETZGEN CO., CHICAGO.


Kilogauses.
Cast Steel.
Sheet Steel.
Cast Iron.
Iron Curves.
Ampere Turns per Centimeter.
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
7.
8.
9.
8
10
12
14.
16
18
20

The Switchboard.

Since the switchboard is to be for a farm power plant, probably expense will want to be saved even though the board does not look quite so well. Therefore a black slate panel was chosen. A field rheostat with resistance up to 25 ohms will be needed and a main circuit switch designed for 125 amperes and fuses. Since the full load current is 90.9 amperes, the size of ammeter should be 0 to 150 amperes. The normal voltage is 110 volts, therefore a voltmeter reading from 0 - 150 volts would be needed.

Two lamps may be connected across the lines. These lamps are in series and a ground is put in between the two lamps. Their circuit is normally open, but may be closed by means of a push button. The purpose of the lamps is to show a ground on the line, for then when the button is pushed one lamp will burn much brighter than the other. A 110 volt push button is also needed.